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HEC-6: Reservoir Sediment Control Applications

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HEC-6: RESERVOIR SEDIMENT CONTROL APPLICATIONS[1]

Caveat: ". . . the choice of a model at this time is arbitrary, and the choice of a modeler is probably more important than the choice of a model." (Dawdy and Vanoni 1986)

1. Some History of HEC-6 Development and Applications.[2] The following list summarizes efforts of the Corps' Waterways Experiment Station (WES) and Hydrologic Engineering Center (HEC) to improve HEC-6. Note that numerous research and project applications of HEC-6 have been performed by other Corps' offices, government agencies, private consultants, universities, and foreign countries that are not reported here.

- The "Time Sequencing Method" of scour and deposition calculations was developed at the Little Rock District of the Corps of Engineers in 1967 by Tony Thomas; it lead to the development of HEC-6. The motivation for that effort was to confirm land acquisition requirements for Ozark Reservoir on the Arkansas River, recognizing potential future (50-year) sedimentation.

- The next major development to the numerical model that was to become HEC-6 was made at HEC for the Walla Walla District in the early 70's. The need was to predict future water surface elevations for levees at Lewiston ID on Lower Granite Reservoir. The incorporation of bed material sorting and armoring and expansion of the transport of grain sizes up to 64mm was done at this time.

- First complete documentation published by HEC for "Scour and Deposition in Rivers and Reservoirs", 1973.

- First HEC "Sediment Transport" training course presented, 1973.

- The third major development was made in 1974 for the Corps of Engineers' Fort Worth District. They needed to predict future maintenance dredging on the proposed Trinity River Navigation Project which consisted of 22 locks and dams in series. Silt and clay were the dominant sediment classes. The numerical model was modified to handle a system of locks and dams and to transport, deposit, and consolidate clays and silts.

- Comparison of model results with laboratory flume data published in ASCE Hydralulics Division Journal (Thomas and Prasuhn 1977).

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[1] Prepared by D. Michael Gee, Senior Hydraulic Engineer, Hydrologic Engineering Center, 609 2nd St., Davis, California 95616. Published by the Federal Energy Regulatory Commission in *Notes on Sediment Management in Reservoirs: National and International Perspectives*, Edited by Drs. Shou-shan Fan and Gregrory Morris, 31 December 1993.

[2] Contributions to this section by Tony Thomas of the U.S. Army Corps of Engineers Waterways Experiment Station are gratefully acknowledged.

- Use of the model for analysis of scour of sediment deposits after removal of a dam is demonstated (HEC, 1977).

- "Scour and Deposition in Rivers and Reservoirs" is designated as "HEC-6". HEC publishes a user's manual and makes a public release of the model, 1977.

- The next major development was made for the Walla Walla District in 1978 to deal with a dendritic network of streams. This led to the "Network Version" of HEC-6 developed by WES.

- Addition of gravel mining capability at HEC, 1980.

- Addition of graphics using HEC-HGP (Hydraulics Graphics Package), 1980.

- The next major development was devised for studies of the Toutle and Cowlitz rivers responses to the Mt. St. Helens eruption in 1980. This work was performed for the Corps' Portland District during 1980-1985. Several transport functions were added to the model and the capability of including the effect of high concentrations of fines on the transport of sands using Colby's correction factor was added. A normal depth approximation to supercritical flow was developed. These enhancements were made to the Network Version which was given the name "TABS-1" and became the research version of the model at WES.

- Publication of HEC Training Document No. 13, "Guidelines for the Calibration and Application of Computer Program HEC-6", 1981.▸Application of HEC-6 to the Arkansas River, CO. This included simulation of irrigation diversions and use of HEC-DSS for hydrologic data management (Gee 1983).

- Release by HEC of a microcomputer (PC) version of HEC-6, 1985.

- Addition of cohesive sediment erosion algorithms. This was initially made to TABS-1 for Vicksburg District studies of the Red River Navigation Project in 1986.

- Implementation of a commercial vendor system by HEC for software distribution and support outside of the Federal Government, 1988.

- The next major development of TABS-1 was made for studies of the Richard B. Russell Reservoir pump-back hydropower project by the Savannah District. This modification changed geometry files from sequential storage to random access storage.

- A major enhancement was made to TABS-1 for dredging studies in the lower Mississippi River for the New Orleans District in 1991. The rate of dredging could be prescribed as well as the location of the out-fall discharge.

- Documentation and public release of a network version, based on TABS-1, of HEC-6 by HEC, 1991.

- Major update of TD-13, 1992.

- Update of user's manual, 1993.

- Ongoing work at WES with TABS-1 involves coupling of the sediment transport algorithms with the UNET unsteady flow program. It is planned to include the results of this work in the HEC NexGen River Analysis System currently undergoing design and development.

2. HEC-6 Description.

HEC-6 (HEC 1991) is a one-dimensional movable boundary open channel flow and sediment movement model designed to simulate changes in river profiles due to scour and deposition over fairly long time periods (typically years, although applications to single flood events are possible). The continuous flow record is broken into a sequence of steady flows of variable discharge and duration (see Figure 1). For each flow a water surface profile is calculated (using steady flow standard-step backwater computations) thereby providing energy slope, velocity, depth, etc. at each cross section. Potential sediment transport rates are then computed at each section for the given bed material grain size distribution. These rates, combined with the duration of the flow allow for a volumetric accounting of sediment for each reach. The amount of scour or deposition at each section is then computed and the cross section shape adjusted accordingly (Figure 2). The computations then proceed to the next flow in the sequence and the computation cycle is repeated beginning with the updated geometry. The sediment calculations are performed by grain size fraction thereby allowing for the simulation of hydraulic sorting and armoring. Features of the model include: capability to analyze networks of streams (Figure 3), automatic channel dredging, various levee and encroachment options, and several options for computation of sediment transport rates.

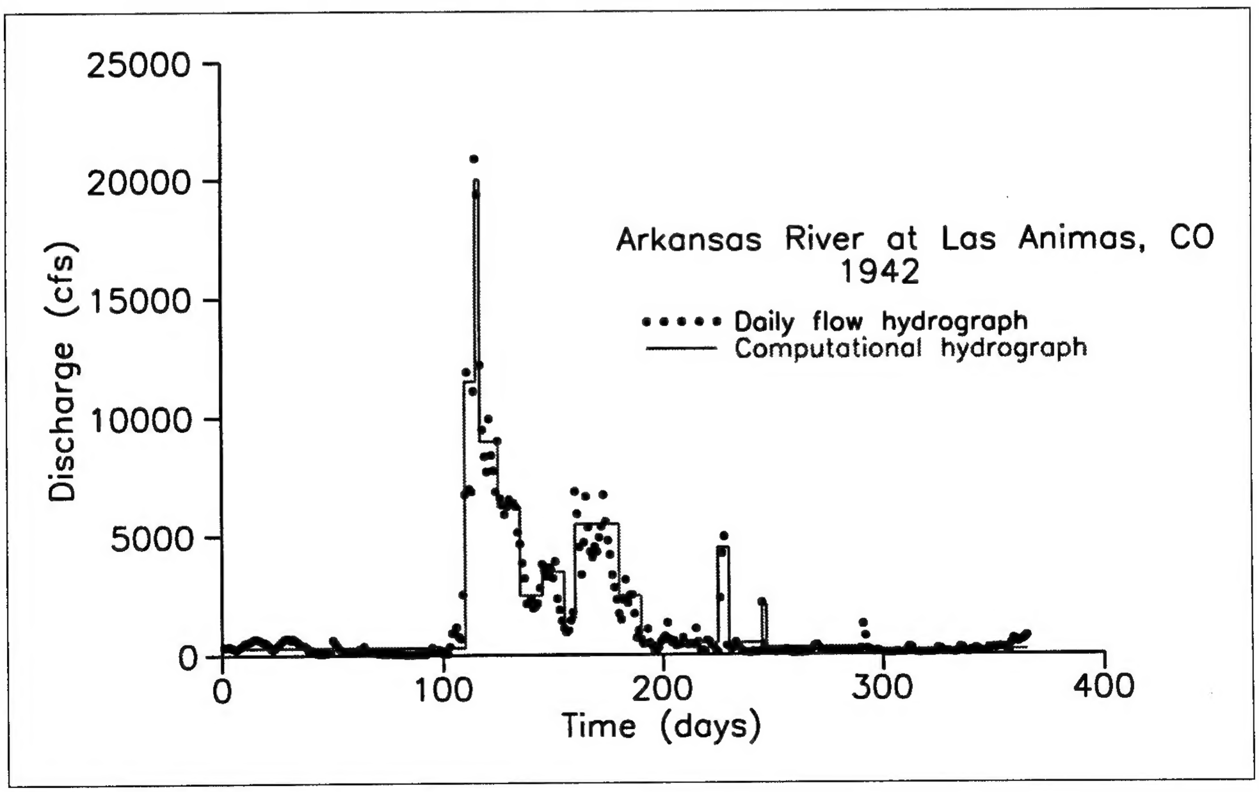

Figure 1 Flow Data Compression

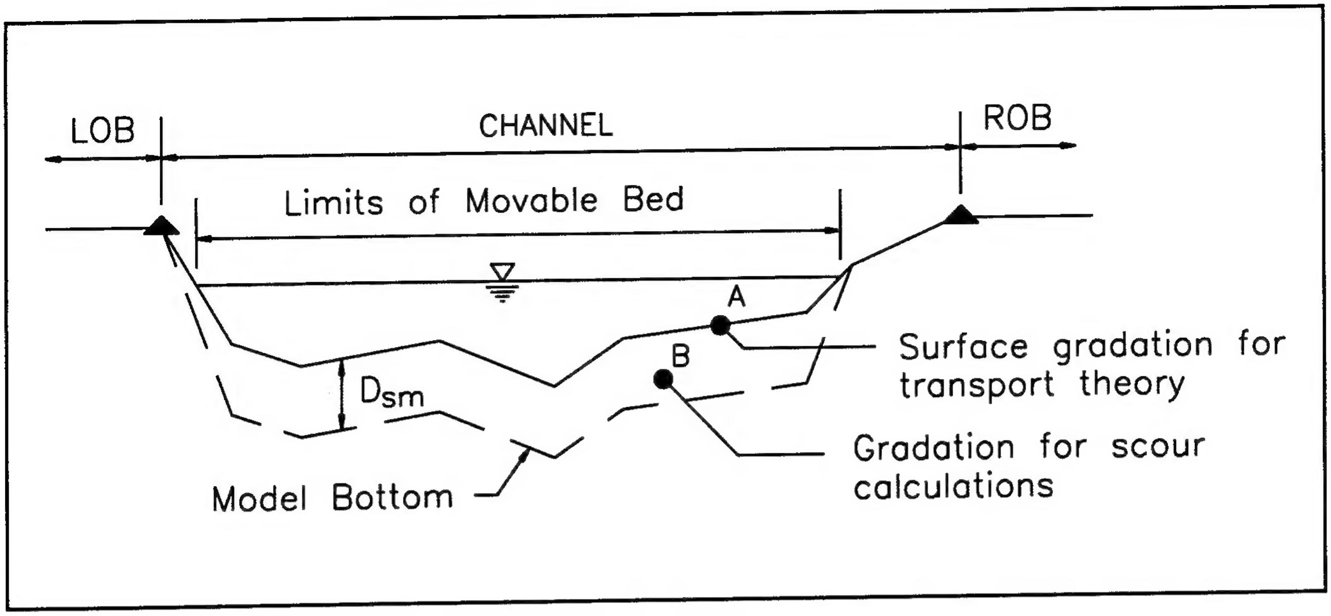

Figure 2 HEC-6 Cross Section Adjustment

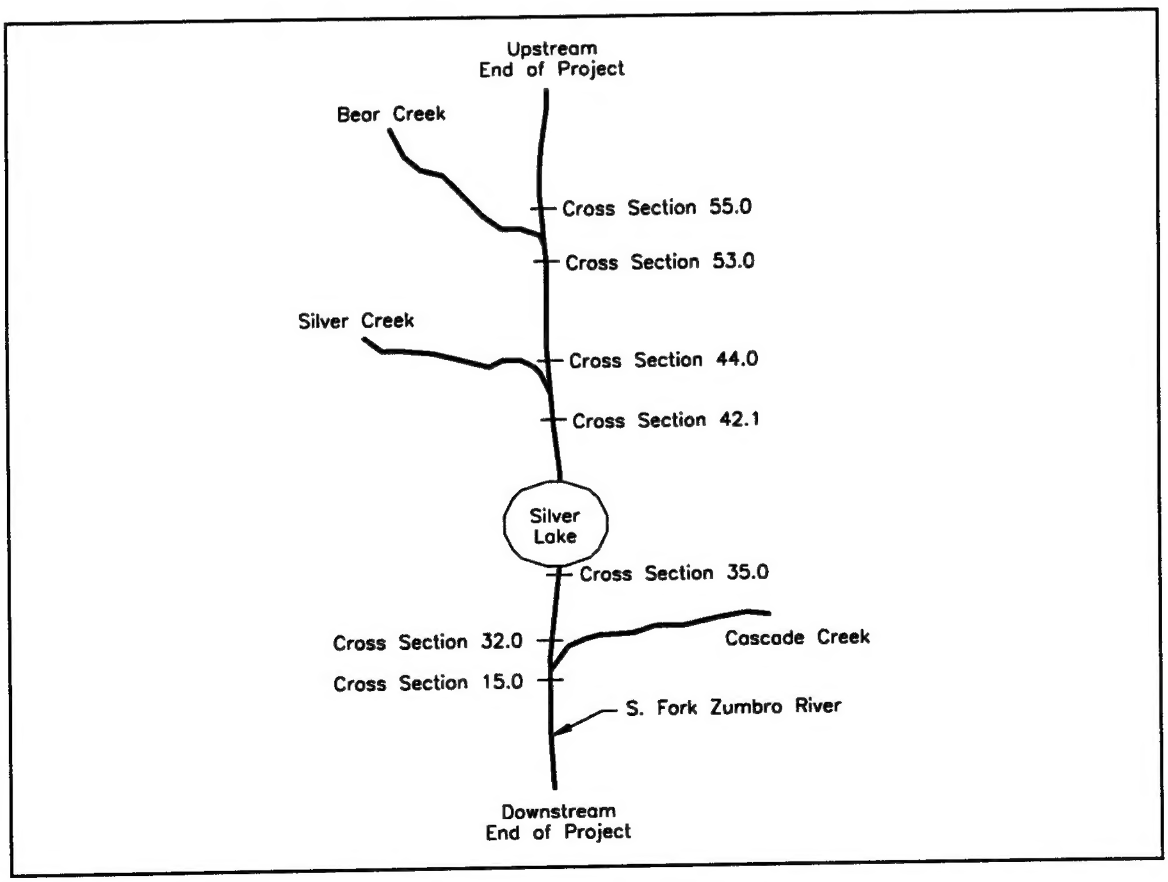

Figure 3 Example Stream System Network

HEC-6 (HEC 1991) is a movable boundary model. It was formulated around Einstein's basic concepts (Einstein 1950) of sediment transport; however, it is designed for the non-equilibrium case. Einstein did not address the non-equilibrium condition, but his "particle exchange" concept was extended in HEC-6 by noting that when sediment is in transport there will be a continual exchange between particles in motion and particles on the bed surface. The residue in the bed may be measurable, as in the case of the "bed material load", or it may be unmeasurable, as in the case of "wash load". The stability of particles on the bed surface may be related to inertia, as in the case of non-cohesive particles; or that stability may be primarily electrochemical, as in the case of cohesive particles. Energy forces acting to entrain a particle may be primarily gravity induced, as in the case of flow in inland rivers; or the forces may be combinations of energy sources such as gravity, tides, waves, and density currents, as in the coastal zone. Different types of sediment require different entrainment functions depending upon the propensity of the sediment to change hydrodynamic and physical properties of the flow and upon the sensitivity of the sediment type to water temperature and chemistry.

a. Equations of flow. The equations for conservation of energy and water mass are simplified by eliminating the time derivative from the motion equation which leaves the gradually varied steady flow equation. It is solved using the standard-step method for water surface profiles. The following terms are included:

$$\frac{\partial h}{\partial x} + \frac{\partial(\alpha U^2/2g)}{\partial x} = S_e \qquad \text{(conservation of energy) (1)}$$

where

g	=	acceleration due to gravity
h	=	water surface elevation
S_e	=	slope of energy line
U	=	flow velocity
x	=	distance in the direction of flow
α	=	correction for transverse distribution of flow velocity

$$Q = UA + Q_1 \qquad \text{(conservation of water) (2)}$$

where

A	=	cross-sectional area of flow
Q_1	=	lateral or tributary inflow
Q	=	main stem water discharge downstream from Q_1
U	=	main stem mean water velocity upstream from Q_1

b. Friction and form losses. Both friction and form losses are included in S_e; bed roughness is prescribed with Manning *n* values. *n* values may vary with water discharge, location, or be related to bed material size (Limerinos 1970).

c. Equation of sediment continuity. The Exner equation is used for conservation of sediment:

$$\frac{\partial Q_s}{\partial x} + B_s\frac{\partial Y_s}{\partial t} - q_s = 0 \qquad \text{(conservation of sediment) (3)}$$

where

B_s = width of bed sediment control volume
Q_s = volumetric sediment discharge rate
q_s = lateral or tributary sediment discharge rate
t = time
Y_s = bed surface elevation

d. Equation of sediment transport. Einstein's (Einstein 1950) work is definitive and presents a complete view of the processes of equilibrium sediment transportation; it, however, has been more useful for understanding those processes than for application, partially because of the numerical complexity of the computations. Many other researchers have contributed sediment transport functions - always attempting to develop one which is reliable when compared with a variety of field data. The resulting functions are numerous, yet no single function has proved superior to the others for all conditions. Therefore, the following functional form is presented here to show the importance of various parameters.

$$G = f\,(U,\ d,\ S_e\ ,\ B,\ D_{eff}\ ,\ SG_s\ ,\ G_{sf}\ ,\ D_{si}\ ,\ P_i\ ,\ SG_f\ ,\ T,\ ...) \qquad \text{(Sediment Transport)} \quad (4)$$

where:

B = effective width of flow
d = effective depth of flow
D_{eff} = effective particle diameter of the mixture
D_{si} = geometric mean of particle diameters in each size class i
G = total bed material discharge rate in units of weight/time (e.g., tons/day)
G_{sf} = grain shape factor
P_i = fraction of particles of the i^{th} size class that are found in the bed
S_e = slope of energy grade line
SG_f = specific gravity of fluid
SG_s = specific gravity of sediment particles
T = water temperature
U = flow velocity

Sediment transport rates are calculated for grain sizes up to 64 mm (<u>soon to be expanded to 2000 mm</u>). Sediment sizes larger than 64 mm, that may exist in the bed, are used for sorting computations but are not transported. For deposition and erosion of clay and silt sizes up to 0.0625 mm, Krone's (1962) method is used for deposition and Ariathurai's (1976) adaptation of Parthenaides' (1965) method is used for scour. The default for clay and silt allows only deposition using a method based on settling velocity.

The sediment transport function for bed material load is selected by the user. Transport functions available in the program include the following:

a. Toffaleti's (1966) transport function
b. Madden's (1963) modification of Laursen's (1958) relationship
c. Yang's (1973) stream power for sands
d. Duboys transport function (Vanoni 1975)
e. Ackers-White (1973) transport function
f. Colby (1964) transport function
g. Toffaleti (1966) and Schoklitsch (1930) combination
h. Meyer-Peter and Müller (1948)
i. Toffaleti and Meyer-Peter and Müller combination
j. Madden's (1985, unpublished) modification of Laursen's (1958) relationship
k. Parthenaides (1965), Ariathurai (1976) and Krone (1962) for cohesive sediments

l. Copeland's (1990) modification of Laursen's relationship (Copeland and Thomas 1989)
m. User specification of transport coefficients based upon observed data

e. Computational methodology. Descriptions of the computational methodology used in HEC-6 and application of the program are presented in the HEC-6 user's manual (HEC 1991).

Experience has shown that successful application of movable boundary models may require substantial effort to reproduce field observations, i.e., calibration. The general topic of application and calibration of numerical river models is thoroughly covered in Cunge, et al. (1980).

3. Specific Reservoir Simulation Capabilities.

- User can specify water surface elevations (internal boundary conditions) to simulate operation and control of reservoir pool elevations as functions of time.

- Allows for deposition and compaction of cohesive sediments with time.

- Provides for reentrainment of cohesive sediments based on equations presented by Parthenaides (1965).

- Can simulate deposition at various pool levels and, therefore, compute impacts of reservoir deposits on upstream water surface profiles.

- Has a "parallel flow" capability, which means that several discharges in the time series of flows can be modeled without updating boundary geometry - achieves computational efficiency.

- Can compute trap efficiencies and perform volumetric accounting of sediment by grain size.

4. Some Limitations of HEC-6 with Regard to Reservoirs.

- It is a **one-dimensional** model.

- Density variations due to thermal stratification or sediment concentrations are not included in the hydraulics.

- Modeling of the structure is limited by what the user can do with cross sections and water surface elevations.

5. Some Additional HEC and Corps of Engineers Software for Reservoir Analysis.

- HEC-5 "Simulation of Flood Control And Conservation Systems" (HEC 1982).

- HEC-5Q "Simulation of Flood Control and Conservation Systems - Appendix on Water Quality Analysis" (HEC 1986).

- HEC-PRM "Prescriptive Reservoir System Analysis Model - Missouri River System Application" (HEC Technical Paper No. 136 Nov. 1991).

- HEC NexGen project.

- TABS-2 "Open Channel Flow and Sedimentation," two-dimensional flow and sediment modeling system (vertically averaged).

a. Purpose. The purpose of the TABS-2 system (Thomas and McAnally, 1985) is to provide a complete set of generalized computer programs for two-dimensional numerical modeling of open-channel

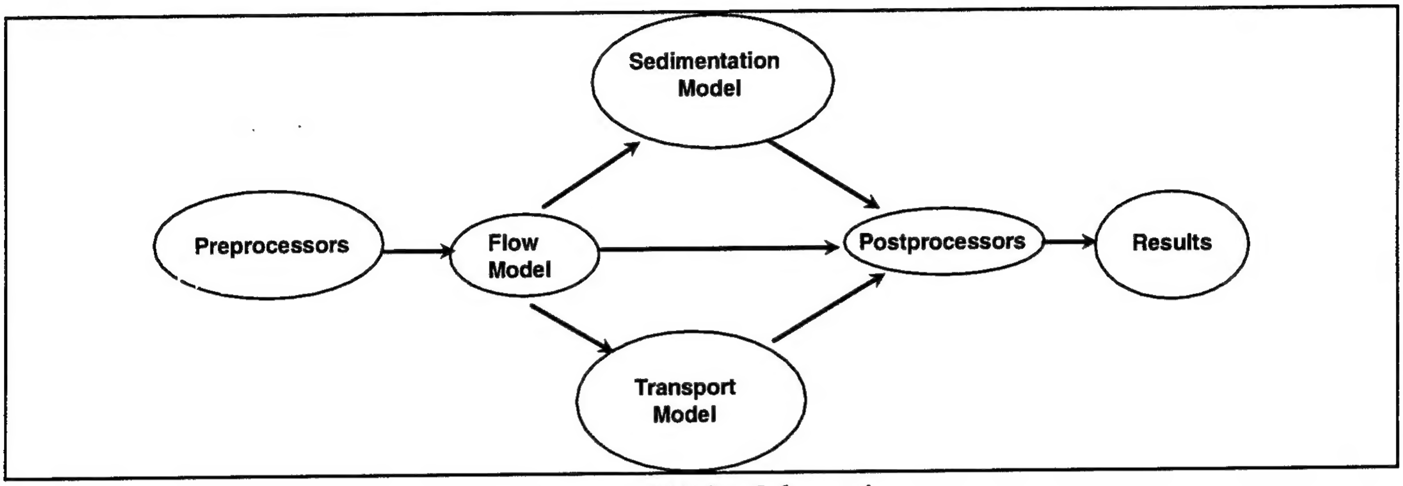

Figure 4 TABS-2 Schematic

flow, transport processes, and sedimentation. These processes are modeled to help analyze hydraulic engineering and environmental conditions in waterways. The system is designed to be used by engineers and scientists who need not be computer experts.

b. Description. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation processes in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure 4.

c. Uses. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, dispersive transport, sediment erosion, transport and deposition, resulting bed surface elevations, and feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact of project designs on flows, sedimentation, and salinity. The calculated velocity pattern around structures and islands is particularly useful.

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A review of the historical development of HEC-6 is given. A description of the model capabilities theory, and data requirements is provided. Emphasized throughout is application of HEC-6 to reservoir sediment analysis.

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